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Estimating uncertainty of 2D hydraulic models used for aquatic habitat modeling studies

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Abstract

Spatially-distributed depth and velocity predictions are required for habitat-based instream flow studies. The purpose of this thesis is to estimate uncertainty of two-dimensional (2D) depth-averaged hydraulic models when applied with close spacing of computational nodes. Motivation for close node spacing is discussed from the ecological, aquatic habitat perspective. Model-generated maps of predicted depth and velocity require sufficient resolution to capture spatial variations relevant to aquatic habitat; however, bathymetric variations at that resolution are more complex than strictly applicable for the depth-averaged hydrostatic model equations. Hydraulic model assumptions are discussed and the geometry of a typical model is analyzed to identify areas that do not conform to assumptions.

Model input data, including bathymetry, water surface elevation, flow rate, depth and velocity measurements, have accuracy within 5% of actual values. Accuracy of depth measurements conducted with a boat-mounted echosounder approach 15 centimeters and are the greatest source of uncertainty for depth error in model predictions. For model test scenarios using the RMA2 2D depth-averaged finite element code, geometries exhibiting slopes greater than 0.10 (ratio of rise to run) or exhibiting abrupt lateral changes in width are shown to cause changes in continuity (velocity conservation) of greater than 2.5%. For a calibrated model of the Brazos River, Texas, 95% of the model area exhibited low uncertainty with continuity deviations less than 2.5%; remaining areas exhibited higher uncertainty resulting from steep slopes or high Froude numbers.

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1.0 Introduction

1.1 Purpose

Habitat-based instream flow studies require spatially-distributed depth and velocity information. Aquatic habitat predictions use output from two-dimensional (depth-averaged), free-surface, hydrostatic, numerical hydraulic models. Model-generated maps of depth and velocity predictions must capture spatial variations relevant to aquatic habitat; however, the necessary spacing between computational nodes is often closer than this class of numerical hydraulic models can address due to limitations of the hydrostatic approximation.

The purpose of this thesis is to estimate uncertainty of two-dimensional (2D) (depth-averaged) hydraulic models with close spacing of computational nodes. River bathymetry exhibits substantial variability when viewed on a small length scale (e.g., 1 to 5 meters for a 100 meter wide river); exposing that variability by using close model node spacing forces a hydrostatic model to compute flow in local areas under what are arguably non-hydrostatic conditions. Although a river reach at the larger scale may generally conform to hydrostatic approximation, local areas may exist that do not conform. The modeler aware of these issues can assign node spacing appropriate for conditions; however, guidance in setting node spacing is model dependent. The affect of node spacing on the hydrodynamic results has been previously quantified for only limited model applications at the aquatic habitat scale (Crowder and Diplas 2000; Horritt et al. 2006).

In this thesis, expectations on node spacing are discussed from the perspective of hydraulic model application to aquatic habitat studies. Hydraulic model assumptions are discussed and areas that do not conform to assumptions are identified within a completed hydraulic model.

1.2 Motivation

Instream flow studies are multi-disciplinary studies that determine relationships between ecological health and river flow regime (Stalnaker et al. 1995; Bovee 1998; Annear et al. 2002; NRC 2005; TIFP 2006). The purpose of such studies is to determine the quantity and timing of flow necessary to maintain the health of the ecosystem, so that additional water can be made available for human use.

Many studies use aquatic habitat as one link between ecosystem health and flow regime (e.g., Guay 2000; Bowen et al. 2001; Bunn and Arthington 2002; Bowen et al. 2003; Hardy et al. 2003; Katopodis 2003; Olsen et al. 2003; Olsen et al. 2004; Osting et al. 2004a; Osting et al. 2004b; Hardy 2006), and development of an aquatic habitat model is one way to quantify the change in habitat resulting from change in flow (Stalnaker et al. 1995; Annear et al. 2002; NRC 2005; TIFP 2006). Aquatic habitat is typically defined within ranges of a number of components including substrate (e.g., bed material), cover (e.g., undercut banks), structure (e.g., large woody debris), water temperature, water depth, water velocity and other environmental variables that aquatic species utilize during their life cycle (Bovee et al. 1998; Vadas and Orth 1998; TIFP 2006). Because of the spatial heterogeneity of each of these components over an entire river, the river is typically divided into major segments having similar characteristics and instream flow guidelines are be developed separately for each major segment. Within each major segment, a short river reach (or a collection of short reaches) is typically studied in detail (Stalnaker et al. 1995; NRC 2005; TIFP 2006). The distribution of habitat within the collection of short reaches should be reflective of the distribution of habitat found within the major segment (Stalnaker et al. 1995; TIFP2006).

By collecting field data within a short reach on each of the habitat components (listed in the previous paragraph) and mapping their distribution, the location and area of each type of aquatic habitat can be determined (Bovee et al. 1998; TIFP 2006). Arguably, most habitat components at any particular discrete location within a river reach change little across the range of flows below flood levels; indeed, aquatic habitat modeling methods rely on this argument (Bovee et al. 1998; TIFP 2006). For example, the geometry of a boulder, a patch of gravel or an undercut bank remain largely unchanged in the same location as flow rate within the channel decreases from 60th percentile of flow occurrence to 25th percentile (e.g., from 2000 cfs to 500 cfs). However, for the same change in flow rate, the changes in local velocity and depth can be an order of magnitude. Since resources (manpower and finances) are generally not available to measure velocity and depth within all habitats for the entire range of flow rates, a limited depth and velocity dataset is typically collected at a few locations for a few different flow rates (Bovee et al. 1998; TIFP 2005). This limited (although still voluminous) data set is used to calibrate a hydraulic model of the river reach.

A multi-dimensional hydraulic model, e.g., a 2D depth-averaged model, is useful for habitat analysis since it can predict water depth and average water column velocity at many thousand user-specified locations within the boundaries of the study site (Leclerc et al. 1995; TIFP 2006). Compared to the quantity of output points, the quantity of data input necessary to run the model is small (Austin and Wentzel 2000). Inputs required for a 2D model for a subcritical river reach include a bathymetric data set of the submerged river bed, upstream flow rate and downstream water surface elevation (Donnell et al. 2005; TIFP 2006). Using a rating curve developed for the project site to relate elevation to flow rate, the model can predict velocity and depth for the entire range of flow rates that are of interest within the context of the instream flow study (Leclerc 1995; Bovee et al. 1998; TIFP 2006).

As outlined above, 2D hydraulic models appear to be efficient tools capable of providing depth and velocity information as required by instream flow aquatic habitat models (Leclerc 1995). However, many factors can potentially affect and arguably undermine the accuracy of model output including model formulation assumptions; model numerical solution limitations; accuracy and resolution of input data; and user-specified spacing between model solution points (Donnell et al. 2005; Pasternack et al. 2006). Compounding the potential for uncertainty, models can converge to a stable solution, implying that the model has successfully calculated flow fields even though the model output may be neither reasonable nor correct (Richards 1990).

Although a definitive quantification of model error is beyond the scope of this work, the motivation for this thesis lies in determining the potential magnitude of depth and velocity error, hereafter referred to as uncertainty, contributed by each factor. Characteristics of 2D hydraulic models are described within the context of instream flow studies presented in literature; pertinent hydraulic modeling assumptions are described and critical test cases identified; accuracy of input data is discussed; and historical case studies are described. A new dimensional analysis is developed to relate geometry of previous uncertainty studies to geometry expected in an instream flow hydraulic model. Finally, a new series of spatial statistics are defined to quantify and identify areas that are most prone to accuracy problems within a calibrated hydraulic model.

1.3 Need for spatially-distributed flow information

Quantification of aquatic habitat is the basis of many instream flow studies (Bovee et al. 1998, Annear et al. 2002, Bunn and Arthington 2002; Katopodis 2003; Leclerc et al. 2003). Across a range of flow rates, 2D hydraulic models can predict depth and velocity, two key components of aquatic habitat.

Ideal spacing of model computational locations (nodes) resolves variations in depth and velocity at a scale relevant to organisms utilizing that habitat (Leclerc et al. 1995, Vadas and Orth 1998, Crowder and Diplas 2000; Katopodis 2003). Nodes are discrete points where the model performs calculations and outputs predictions (Figure 1.1). Depending on the type of model (e.g., finite difference or finite element), the collection of nodes can be regularly spaced or arranged irregularly (e.g., Figure 1.1).

To quantify how aquatic organisms utilize habitat, both laboratory and field studies have been conducted by other researchers and are described in literature (Vadas and Orth 1998; Grossman et al. 2002). In a laboratory, Grossman et al. (2002) identified optimum focal point velocity in addition to a number of other factors such as cover, substrate, temperature and food source which are not further addressed in this thesis. Such laboratory studies provide data that could be used to justify definition of aquatic habitat on size scales similar to the size of minnows (5 to 7 cm), the organisms that are typically studied in a laboratory because they do not require large tanks in the laboratory.

While laboratory studies do provide insight into size of optimum habitat under controlled conditions, habitat utilization must be validated in the field since each natural system and each organism's adaptation to that system is unique (NRC 2005). Field sampling of organisms within their habitat may be conducted using a variety of equipment, such as kick nets for benthic species, and hoop nets, traps, seines, gillnets and electroshockers for fish (Bovee 1998; TIFP 2006). Of those, the smallest habitats sampled are by the kick nets and minnow traps at roughly 0.5 square meters of surface area. Seines and electroshockers sample larger areas, from 20 sq. meters up to 27 sq. meters of surface areas for 4.6m and 9.1m seines, respectively (TIFP 2006). Gillnets set in the vertical plane roughly 2 meters high and up to 20 meters long can sample much larger areas (TIFP 2006); however, sampled horizontal-plane surface area is difficult to quantify since these nets require fish movement to affect catch. At least one study used 10 square meter bio-grids to delineate sampling areas (Mosier and Ray 1992).

Compared to the relatively small dimension of habitat quantified in the laboratory, the length scale of field-sampled habitat is more relevant for instream flow studies. Therefore, for purposes of habitat modeling, the standard grid spacing of hydraulic model grid nodes should arguably be proportional to the size of the smallest field-sampled habitat that corresponds to habitat sampled by a 4.6 m long seine. Further, a nearer node spacing (2.3 meters for example) provides smoother lateral transitions between adjacent habitats. Alternatively, node spacing could be relaxed to a level “based upon appreciation of the length scales within the flow” (Hardy et al. 1999); areas to which this relaxation criterion is applicable include areas where both habitat and flow patterns are uniform across a wide range of flow rates.

Recent studies have found that less than 50% (often less than 30%) of the variability in organism abundance can be attributed to velocity, depth and substrate (Morgan 2002; Gelwick and Li 2002; Li 2003). The uncertainty of the habitat criteria has been argued to be much larger than, perhaps even dwarfing, the uncertainty of depth-averaged hydraulic models (Bhosle, 2004). The take-home message with regard to habitat modeling is that trends, rather than the specific values, of habitat area over a range of flow rates make the habitat models useful. Habitat models should not be considered predictive fish-finders, i.e. maps of habitat model output should not be used to find the best fishing hole for a given flow rate (Osting 2006). In spite of the implication that a well-calibrated hydraulic model may not be necessary within the context of instream flow habitat studies, identifying, quantifying, minimizing and, where possible, removing uncertainty is an explicit objective of instream flow studies (Bovee et al. 1998; NRC 2005; TIFP 2006); therefore, every effort should be made by the modeler to develop a well-calibrated, defensible model.

The following sections in this thesis identify potential sources of uncertainty, quantify magnitudes of uncertainty (where possible) and describe model configurations that may reduce uncertainty. Any discussion herein of model uncertainty is applicable not only to instream flow applications, but also to other model applications of shallow water equation models including water quality and sediment transport studies (King 1992; Berger and Howington 2002; Donnell et al. 2005).

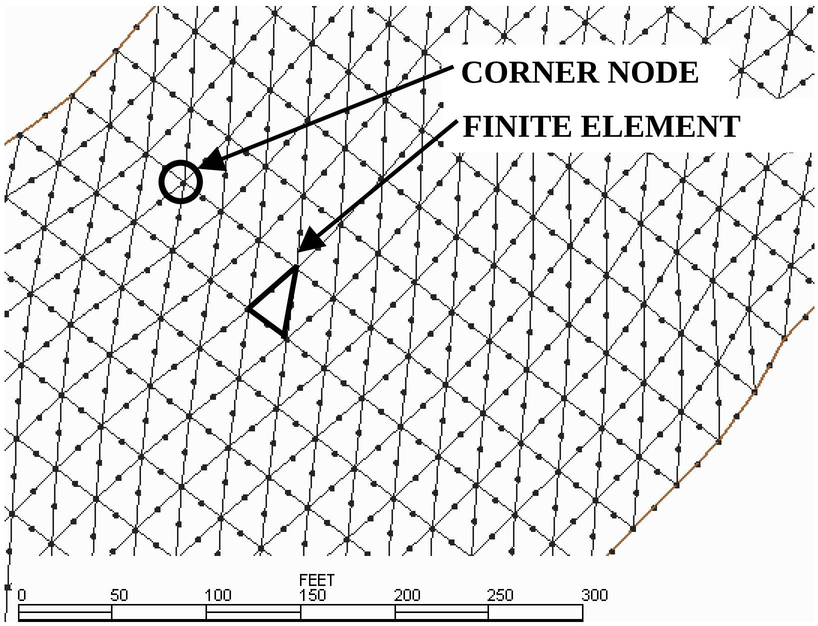


Figure 1.1 - Nodes of a finite element 2D hydraulic mesh

2.0 Two-dimensional hydraulic modeling for instream flow studies

2.1 Applied hydraulic models

Two-dimensional numerical models of the Boussinesq, hydrostatic, depth-averaged Navier-Stokes equations (i.e., the shallow-water equations) have been used for a variety of hydrodynamic studies, including estuarine circulation and salinity migration (e.g., King 1992; King and DeGeorge 1995), flood surfaces (e.g., Bates et al. 1997; Hardy et al. 1998; King and Williams 2000), training structures (e.g. Richards 1990; Freeman 1992) and sediment transport (e.g., Deering 1990; Hodkinson and Ferguson 1998).

Two recent riverine aquatic habitat studies conducted by the Texas Water Development Board (partially funded by the U.S. Army Corps of Engineers) on the Brazos River, Texas (Osting et al. 2004a), and the Sulphur River, Texas (Osting et al. 2004b), employed the finite-element numerical model RMA2 (Donnell et al. 2005). For an aquatic habitat study on the Colorado River, Texas, the finite element numerical model River2D (Steffler and Blackburn 2002) was applied by the author to ten river reaches ranging in length from 1 to 2.5 km (study in progress). Additional recent studies using the 2D shallow water equation models have been completed by a number of research teams (Galagher 1999; Guay et al. 2000; Crowder and Diplas 2000; Bowen et al. 2001; Wagner and Mueller 2002; Hardy 2003; Bowen et al. 2003; Katopodis 2003; Morin et al. 2003; Olsen et al. 2003; Olsen et al. 2004; Orth et al. 2004; Stewart et al. 2005). At least one study has been conducted using a 3D code (Orth et al. 2004). Reported hydraulic model characteristics, descriptions of calibration effort and reports of quantification of uncertainty, are compiled in Table 2.1; if validation measures are reported (often they are not), the error metrics are included in the table.

The minimum level of calibration evident in all modeling studies is matching of water surface elevation at the upstream boundary. Additional calibration is sometimes performed to match measured points of the water surface profile within the modeled reach. In very few cases are hydraulic model validation metrics presented in the literature.

2.2 Shallow water equations

The full 3D Navier-Stokes equation set consists of equations to ensure conservation of mass and conservation of momentum,

$$\frac{\partial u_i}{\partial x_i} = 0 \qquad \text{for } i = 1,2,3 \qquad (2.1)$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = \frac{1}{\rho}\left(-\frac{\partial p}{\partial x_i} + \mu \frac{\partial^2 u_i}{\partial x_j \partial x_j}\right) + F_i \qquad \text{for } i \text{ and } j = 1,2,3 \qquad (2.2)$$

where:
- u = velocity
- t = time
- p = pressure
- ρ = density
- μ = kinematic viscosity
- x = length
- F = external force

subscripts *i* and *j* represent Einstein notation for Cartesian direction.

Solving by direct methods (e.g. Gaussian elimination) the full 3D Navier-Stokes equations for large array problems requires significant computation time for models with many nodes (Lane 1998); therefore, assumptions are made to simplify the mathematical solution of the partial differential equations and reduce computation time.

Table 2.1 - Calibration and validation of instream hydraulic models

Reference	Model and location	Water Surface Elevation	N	Error Reporting Method	Depth	Velocity
Guay et al. (2000)	Sainte Marguite River, Quebec		271	Range	within 15%	overestimate for velocities > 0.7 m/s
				Qualitative		underestimate for velocities < 0.2 m/s
	cf. LeClerc et al. 1990			R-squared	0.85	0.09
Stewart et al. (2005)	RMA2 - Duffy site	Calibrated to WSE	40	R-squared	0.98	0.57
Colorado and Yampa	USU - Clifton site	Calibrated to WSE	60	R-squared	0.73	0.74
Rivers	RMA2 - Corn Lake site	Calibrated to WSE	23	R-squared	0.68	0.91
	USU - Corn Lake site	Calibrated to WSE	26	R-squared	0.65	0.81
Orth et al. (2004)	RMA2 - Smith River	Calibrated to WSE	186	Range	within 10%	well-correlated
				RMSE	0.04 m	0.04 to 0.09 m/s
	CFX (3D) - Smith River	Not calibrated		Qualitative		well-correlated
Wagner and Mueller (2002)	RMA2 - Ohio River			Average % difference		< 0.09 m/s
				Range		max 0.23 m/s
	RMA2 - Ohio River, Site 2			Average % difference		not horrible
				Range		max 0.46 m/s
Hardy (2003)	USU - LaVerkin River	Calibrated to WSE				
Gallagher (1999)	R2D - Trinity River (CA)		13	Average % difference	0.03	0.06
				Range	-0.22 to 0.43	-0.11 to 0.32
				t-stat	0.67	1.26
				p-value	0.5	0.21
	R2D - Trinity River (CA)		45	Average % difference	0.06	0.07
				Range	-0.27 to 0.58	-0.50 to 0.53
				t-stat	0.78	1.77
				p-value	0.43	0.08
Bovee (1998)	PHABSIM	RECOMMENDATION: WSE prediction should be within 10% of observation				
Bowen et al. (2001)	R2D - Green and Yampa Rivers	Calibrated to WSE		Average % difference	Within 3 to 5%	generally within 5 to 10%
Bowen et al. (2003)	R2D - Upper Yellowstone River	Calibrated to WSE WSE ranged from -0.18 to 0.36, Average difference near 0.05m				
Osting et al. (2004a)	RMA2 - Brazos River	Calibrated to WSE		Range		generally 0.05 to 0.1 m/s
Osting et al. (2004b)	RMA2 - Sulphur River Site 1	Calibrated to WSE		Range		generally 0.05 to 0.1 m/s
Osting et al. (2004b)	RMA2 - Sulphur River Site 2	Calibrated to WSE		Range		generally 0.05 to 0.1 m/s
Olsen et al. (2003)	STAGR - Provo River	Calibrated to WSE				
Olsen et al. (2004)	STAGR - Provo River	Calibrated to WSE				
Morin et al. (2003)	HYDROSIM	Calibrated to WSE WSE was within 5 cm		Qualitative		
Pasternack et al. (2006)	FESWMS - Mokelumne River	Calibrated to WSE		Average % difference	Within 21%	Within 29%

Key		
	WSE	Water surface elevation
	Average % difference	Average for all values of difference between prediction and measurement
	Range	Range between minimum and maximum difference between prediction and measurement
	R-squared	R-squared of linear regression between predictions and measurements
	RMSE	Root Mean Square Error of all prediction-measurement pairs
	t-stat	T-test, comparing predictions and measurements
	p-value	Probability that test statistic is are as extreme as measurements
	Qualitative	A narrative description was reported (e.g., "velocity predictions correllated well to measurements")

Using the principle of conservation of mass, eq. (2.1) ideally ensures that the mass entering a discrete volume equals the mass exiting plus the mass accumulating in the volume. The conservation of momentum for incompressible fluid flow, eq. (2.2) are based upon an application of Newton's Second Law where inertial forces inside the control volume are assumed equivalent to the external forces (fluid pressure, gravity and fluid viscosity) acting upon the control volume. This equation is implemented by balancing shear stresses acting upon the control volume with changing inertia within the control volume.

Water is assumed to be an incompressible liquid, which simplifies calculations by implying a constant control volume with a constant density. In typical situations, the fluid density within the system is assumed to vary negligibly around a constant mean density allowing specification of a system-wide reference density (Bousinesq's approximation). Additionally, hydrostatic (or shallow water) models assume the non-hydrostatic pressure gradients have negligible effect on the resolved flow field. The hydrostatic approximation simplifies the momentum equations by removing the non-hydrostatic pressure term; however, its application implies that rapid changes in the resolved velocity should not occur and vertical accelerations do not affect modeled flow dynamics.

To further simplify the numerical solution, the Reynolds (1895) time-averaging approach is applied, which separates high-frequency fluctuations of velocity (Reynolds' stresses) from the average or background magnitude. An eddy viscosity turbulence model is introduced to characterize turbulent dissipation caused by Reynolds stresses.

The 2D models used for instream flow studies are of the depth-averaged form (rather than homogenously layered) and solve for depth and vertically-averaged velocity within each control volume. By integrating the x and y horizontal components in the vertical z direction, the vertical velocity is removed from the model except for the rate of change of the free surface in unsteady problems. Depth-averaging has the additional implication that the external friction force caused by bed roughness is distributed to the entire water column.

Application of the simplifications noted above yield the shallow water equations, presented here in the form utilized by the RMA2 model (Donnell et al. 2005),

$$\frac{\partial h}{\partial t} + h\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) + u\frac{\partial h}{\partial x} + v\frac{\partial h}{\partial y} = 0 \quad (2.3)$$

$$h\frac{\partial u}{\partial t} + hu\frac{\partial u}{\partial x} + hv\frac{\partial u}{\partial y} - \frac{h}{p}\left(\varepsilon_{xx}\frac{\partial^2 u}{\partial x^2} + \varepsilon_{xy}\frac{\partial^2 u}{\partial y^2}\right) + gh\left(\frac{\partial a}{\partial x} + \frac{\partial h}{\partial x}\right) + h\tau_x = 0 \quad (2.4)$$

$$h\frac{\partial v}{\partial t} + hu\frac{\partial v}{\partial x} + hv\frac{\partial v}{\partial y} - \frac{h}{p}\left(\varepsilon_{yx}\frac{\partial^2 v}{\partial x^2} + \varepsilon_{yy}\frac{\partial^2 v}{\partial y^2}\right) + gh\left(\frac{\partial a}{\partial y} + \frac{\partial h}{\partial y}\right) + h\tau_y = 0 \quad (2.5)$$

where:

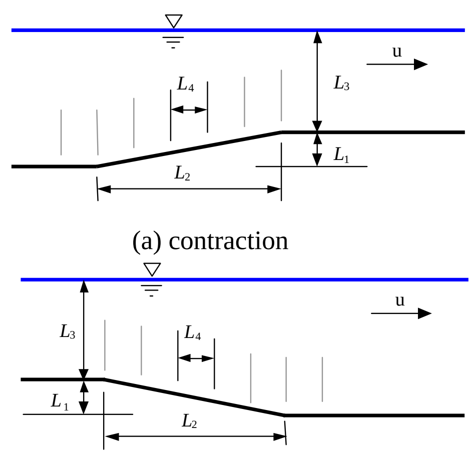
where:	h	= depth of water
	a	= elevation of bottom
	x, y	= Cartesian directions
	u, v	= velocity in Cartesian directions
	t	= time
	g	= acceleration due to gravity
	ε	= eddy viscosity coefficient
	τ	= external forces that include bottom roughness, wind shear and earth's rotation.

In application, a mesh (or grid) composed of a collection of discrete nodes (cf. Figure 1.1) arranged in three dimensions (Cartesian x and y; with bathymetry and water surface elevation measured in the vertical direction, which is not necessarily orthogonal to x and y) is used to represent the collection of control volumes to which the shallow-water equations are applied. The mesh represents the river bed surface and is the bottom no-flow boundary for the model. Velocity and depth are calculated iteratively at each node based upon modeler-specified inputs (eddy viscosity, roughness, upstream flow rate, downstream water surface elevation) and upon velocity and depth in adjacent nodes. Eddy viscosity and bed roughness are generally used to calibrate the model output to match observed field data (Donnell et al. 2005). Models are executed in steady-state mode for discrete flow rates within the full range of interest.

The shallow water equations may not be applicable to complex local features in a larger system, even though the larger system conforms to all assumptions. For example, flow near an isolated feature (e.g., a boulder, submerged tree, a steep dune) within a river may be locally non-hydrostatic over the length-scale of the feature (Berger 1990; Johns 1991). Specification of close node spacing, where such spacing resolves irregular bathymetric features, can increase the number of local areas the shallow water equations were not intended to solve (Lane and Richards 1998). While models can converge to a stable solution implying that the model has successfully calculated flow fields, the output is not necessarily correct (Richards 1990). Conversely, specification of extremely close node spacing, accurate bathymetry and careful calibration can yield model predictions representative of observed conditions for complex flow features such as obstructions (Crowder and Diplas 2000).

One potential cause for model error is the hydrostatic pressure assumption which requires the vertical scale of flow to be negligible compared to the horizontal scale; more specifically, vertical pressure gradients and vertical accelerations (e.g. at locally-steep slopes or flow separations near a slope face) are not modeled by the shallow water equations (Johns 1991; USACE 1993; Berger 1994; Stansby and Zhou 1998). Therefore, even when node spacing is close enough to resolve locally-steep features, depth-averaged model output may not match velocity that occurs in the field. (e.g. Johns 1991; Stansby and Zhou 1998).

Differences between hydrostatic and non-hydrostatic 2D laterally-averaged (vertical plane) model predictions have been documented (Table 2.2) over a sand dune's lee with slope (L2/L1, see Figure 2.1b) of 0.28 for L1/L3 of 0.4 and Froude number of 0.27; prediction differences were less pronounced on the dune's upstream side with slope 0.1 (Johns 1991). Differences between hydrostatic and non-hydrostatic model predictions (again, for 2D laterally-averaged models) have also been documented on slopes of 0.2 where L1/L3 is 0.5 and Froude number is 0.42, and on slopes of 0.5 and 1.0 where L1/L3 is 0.086 and Froude number nears 1 (Stansby and Zhou 1998). In all cases the difference was more pronounced on lee slopes (Johns 1991; Stansby and Zhou 1998). The characteristic difference in flow pattern is that the non-hydrostatic models predict a flow separation occurring near the bed at the toe of the slope; the hydrostatic models do not predict this separation because of the simplification where the non-hydrostatic pressure term is removed from the momentum equation.



(b) expansion

Figure 2.1 - Vertical contraction (a) and expansion (b)

Table 2.2 - Conditions where differences were observed when comparing hydrostatic and non-hydrostatic 2D laterally-averaged (vertical plane) model predictions

Reference	Slope	L1/L3	Fr	Note
Johns (1991)	0.28	0.4	0.27	Expansion, lee side of dune
	0.1	0.4	0.27	Contraction, stoss side of dune
Stansby and Zhou (1998)	0.2	0.5	0.42	Submerged trench*
	0.5	0.086	1	Submerged trench*
	1	0.086	1	Submerged trench*
				*differences more pronouncedon lee side

Secondary circulation near the concave bank of river bendways exhibits local vertical velocities and affects local changes in water surface elevation (Maynord 1992; Finnie et al. 1999), which the shallow water equations do not model. Models capable of correcting velocity for streamwise vorticity are available (Bernard and Schneider 1992; Jin and Steffler 1993; Finnie et al. 1999). Although Donnell et al. (2005) and Lane and Richards (1998) describe vorticity corrections applied to natural cross-sections as generally negligible, Rodriguez et al. (2004) find the vorticity correction in a natural sinuous river improves the predictions of a 2D depth-averaged model compared to field data and to predictions of a fully 3D model.

In addition to physical reasons that model predictions can be incorrect, node spacing and arrangement can affect accuracy of model predictions (King 1992). Quantitatively-validated rules do not exist for specifying node spacing for 2D depth-averaged shallow-water models to obtain grid-independent predictions; however, some general rules-of-thumb are 1) node spacing should not be nearer to each other than the depth of flow; 2) the angle between nodes in a finite element mesh should be between 45 and 135 degrees; 3) the change in node spacing should be no larger than 30%; 4) spacing should be closest in the direction of strongest depth or velocity gradient; 5) the area of adjacent finite elements should not differ by more than 50%; 6) length to width ratio of a finite element should not exceed 10; 7) triangular or quadrilateral finite elements shapes should not be highly distorted; 8) bathymetric elevations of finite element corner nodes should lie in a plane; 9) finite element edge depths should not change more than 20%; and 10) boundary elements should not exhibit angles greater than 25 degrees (King 1992; Lane and Richards 1999; Katopodis 2003; Donnell et al. 2005).

Coarse node spacing was found to have a greater effect on model predictions than varying the input parameter of bed roughness when length-to-depth ratios were between 20 and 2 (Hardy et al. 1999). Bates et al. (1997) show models with node spacing with length to depth ratio of 15 yield better predictions than models with length to depth ratio of 50. Closer node spacing is assumed to improve model output (Hardy et al. 1999) until node spacing nears the depth of flow, i.e. the length-to-depth ratio nears 1.0 (Katopodis 2003). Crowder and Diplas (2000), however, reports reasonable RMA2V model predictions (but no match to field measurement is reported) near flow obstructions where node spacing is 8 cm and length-to-depth ratio ranges between 0.06 and 0.16.

From a physical (rather than numerical) perspective, morphological aspects of river channels should also be considered when determining node spacing. At reduced flow when water level in the channel is low, the width of the channel may narrow and threading around bathymetric high points may occur. Node spacing across the channel must be sufficiently close to quantify channel width at the lowest flow of interest. As a rule of thumb, a minimum of 13 evenly-spaced nodes should be placed between the water edge at highest flow modeled (15 nodes including edge nodes); this allows a low flow channel width 15% of highest flow channel width to contain hydraulic model output of at least two nodes. Using an example of a channel where high flow events exhibit top widths of 100 m, a low flow channel exhibiting top width of 15 m would have model depth and velocity predictions at two nodes.

2.3 Input data quality

The largest source of uncertainty in shallow-water equation models is the input data (Carter and Shankar 1997; Lane et al. 1999; Crowder and Diplas 2000; Pasternack et al. 2006). Data sets required for development and calibration of a shallow water equation model include bathymetry (submerged topography), roughness, water surface elevation, depth, velocity and flow rate (Donnell et al. 2005); each data type is measured using a different method and each method imparts its own potential error to the measurement.

The hydraulic model mesh (cf. Figure 1.1), representing the river channel bottom in three dimensions, is defined based upon elevation at location data collected in the field at the study site. A typical model domain for habitat modeling encompasses approximately one bankfull width and a length encompassing one or two meander wavelengths (Leopold and Wolman 1957; USGS 2001; TIFP 2006). In larger river systems the domain can be more than 100 m wide and 2,000 m long (Bowen 2003; Hardy et al 2003; Osting et al 2004a; Osting et al 2004b).

Measuring bathymetric field data over large domains requires significant resources, which limits the amount of data that can be collected (Pasternack et al. 2006). Numerous methods of measuring bathymetric data are available, e.g. total stations, boat-mounted echosounders, aerial photogrammetry or LIDAR. Considering that resources will rarely if ever be available to conduct a field survey to characterize every nuance of river bed topography, or to measure elevation at the exact location of each model node, interpolation of elevation field data to model nodes is required.

The modeler's confidence in an elevation assigned to a node is more uncertain when the only available elevation field data is located some distance away from the node; therefore, the spacing between bathymetric field data points (or lines) should be similar to the density of model nodes (Horritt et al. 2006). The maximum feasible distance between node and field data is a judgment call based upon bed surface gradient and complexity as well as method used to interpolate grid node elevation; however, node elevation has been interpolated with reasonable accuracy when the node is located nearer to field data than one quarter of bankfull width (Osting 2004).

Vertical and horizontal accuracy of bathymetric field data is also a consideration; however, since accuracy is better than 20 centimeters (cm) in the vertical and 1 meter in the horizontal (TIFP 2005; Hardy 2003; Osting et al 2004a; Omnistar 2005; Knudsen 2005), node spacing farther apart than 1 meter is not limited by field data measurement accuracy (Horritt et al. 2006). The accuracies noted above are a composite of based upon 2 cm accuracy in water surface elevation measurement (automatic level), 15 cm accuracy in echosounder depth measurement (conservative estimate based upon sounder resolution of 1% depth, boat rocking, soft substrate and shallow depths) and better than 1 meter accuracy of real-time differentially corrected global positioning system (Omnistar 2005). In areas where very close grid spacing is desired, survey equipment exists (Trimble 2005, survey-grade 5800 systems, or a typical total station) theoretically capable measurement accuracies of better than 1 cm vertical and 0.5 cm horizontal; however, vertical accuracy of 2 to 3 cm and horizontal accuracy of 1 cm is a more practical expectation based upon personal experience under ideal conditions.

Water surface elevation is specified as a boundary condition at the downstream boundary and flow rate is specified at the upstream boundary. Water surface elevations are typically measured using either a survey-grade differential GPS system and/or a traditional level. Elevation measurements are typically accurate to 1 or 2 cm (Pasternack et al. 2006; Trimble 2006). Location is measured using a variety of methods, including differential GPS, survey-grade differential GPS, bearing and distance (level, total station or laser), triangulation (tape measure) and photography. Positional uncertainty estimates for each method are shown in Table 2.3.

Repeatable accuracy for flow measurements using Acoustic Doppler Current Profilers (ADCP) is within 2% (Muste et al. 2003). Acoustic Doppler Velocipedes were accurate within (1%) and were shown to give measurements as reliable as price pygmy meters tested under the same conditions (Morlock and Fisher 2002). Electromagnetic point velocity meters were shown to be accurate to 3.3 cm/s (Pasternack et al. 2006). These accuracies in velocity and flow measurement can be expected by following standard data measurement procedures (USGS 2004; Oberg et al. 2005).

Table 2.3 - Accuracy of field-collected input data

	Horizontal	Vertical	Flow
GPS (Standard Positioning Service)			
	10m	30m	
DGPS (real time differential)			
	1m to 2cm	3m to 4cm	
PPDGPS (post-proc. diff.)			
	1m to 0.5cm	3m to 1cm	
Level (water surface, topo)			
		2cm	
Total Station (topo)			
	2cm	5cm	
Laser rangefinder (banks)			
	1m *	2m *	
Echosounder (depth)			
	DGPS	15cm	
ADCP (flow, velocity profiles)			
			2%
ADP (point velocity)			
			1%
Electromagnetic (point velocity)			
			3%

* error is in addition to GPS error

2.3.1 Combining datasets

Development of a hydraulic model requires synthesis of many datasets, all with varying degrees of accuracy and precision, which compounds error. The accuracy of multiple data sets is a particular concern when using GPS data and an even higher concern when attempting to validate model predictions. When using GPS, the error in distance and orientation between multiple points measured within the same data set over a limited time interval is generally very low; however, the entire data set may be biased relative to an absolute datum. GPS data measured on different days (or even on the same day) may have different biases when different satellites are in view or weather conditions exist. Use of post-processing and differential correction is necessary to remove shifts that vary over the course of a day-long or multiple-day field effort (Osting 2006).

Uncertainty in the position of both the model and the validation data makes validation of 2D hydraulic models difficult (Hardy 2006; Osting 2006). In areas with significant gradients, differences between model predictions and field data may result solely from comparing data from the wrong place.

2.3.2 Morphology and temporal changes

Habitat modeling generally requires hydraulic modeling for many river flow rates. Measuring flow rates and water surface elevations for boundary conditions and calibration under different flow conditions does not require an inordinate amount of field work. However, re-measuring the bathymetry for each set of flow conditions is simply impractical. Thus, effects of riverbed erosion/aggradation occurring between the time of bathymetry measurement and the time of flow/elevation measurement cannot be represented in the steady-state, fixed-bed hydraulic models used for habitat analysis.

River bathymetric field data is ordinarily collected at high flow rates (i.e. when the river stage is high; TIFP 2006). Bank areas at this stage are inundated, allowing use of a boat-mounted echosounder to efficiently sample depths along the banks. The bathymetry, collected at high flow (90^{th} percentile flow, for example), is used to develop the mesh used to model all flows including very low flows (5^{th} percentile). As bed and bank physical processes may alter the bathymetry between flow conditions (Julien and Wargadalam 1995; Lane and Richards 1999; Chang and Yen 2002), the bathymetry used for low flow may not be as accurate as that used for high flow. Erosion and deposition of sand and gravel material in the river bed is the primary mechanism for bathymetric alteration (Dinehart 2002). At high flow, larger material is mobilized and transported downstream until flow and velocity reduce and the material is deposited. Although the channel may be observed at high flow to be of the smooth, classical u-shape, the cross-section at low flow at the same location may have one or more benches with a flat bottom. At very low flow, the flat bottom may become partially exposed with two or more small rivulets or braids conveying flow. The bed of the rivulets may be lower in elevation than the bed of the u-shaped channel measured at high-flow; therefore, assignment of a measured low-flow water surface elevation may be inconsistent with the bathymetry dataset incorporated into the model. The only way to improve the model is to use additional topography and bathymetry data to change the model mesh to reflect how the bathymetric condition have changed since the initial dataset was measured.

Larger-scale bathymetric changes include bank sloughing or, at the extreme, channel migration may result from flood events. For any case where significant changes to bathymetry occur, the changes need to be incorporated into models prior to calibrating to water surface elevation data.

3.0 Model uncertainty using RMA2

3.1 Description of RMA2

The numerical code RMA2 (Norton, King and Orlob 1973; Donnell et al. 2005) has been used for river, estuary and coastal projects (King 1992; Bates et al. 1997; Finnie et al. 1997; Crowder and Diplas 2000; Donegan et al. 2001; Mussetter et al. 2004; Bhowmik et al. 2004; Rathburn and Wohl 2005). RMA2 version 4.56 is a 2D finite-element numerical model that predicts depth and horizontal velocity components of free-surface, subcritical flows for either steady-state or time-varying problems. Solving the shallow water equations using the Galerkin finite-element method in space can be accomplished on an unstructured grid. A mixed interpolation scheme solves the equations where velocity can vary quadratically between nodes and water surface elevation varies linearly (Berger 1990; Freeman 1992). For time-marching, RMA2 uses a fully-explicit quadratic approximation of the time derivative (Freeman 1992). Eddy viscosity coefficients are used to model turbulence (Donnell et al. 2005). Manning's 'n' or Chezy parameters characterize bottom roughness (Arcement and Schneider 1989). Wind stress forces can be constant or vary with time and Coriolis terms can account for effects of earth's rotation (Donnell et al. 2005). Algorithms to control element wetting and drying improve model stability for initial spin-down and time-varying models (Donnell et al. 2005).

In addition to simplifications applicable to all shallow-water equation models, RMA2 is limited (by its numerical solution scheme) to flow conditions with Froude numbers less than 0.6 (Donnell et al. 2005). For instream flow studies on rivers where shallow, high-velocity areas exist (Vadas and Orth 1998; Crowder and Diplas), RMA2 may never converge to a stable solution.

The typical procedure for calibrating a steady-state RMA2 model is to "spin the model down," i.e., to transition gradually from initial conditions promoting model stability to final conditions where model output matches field observations (Donnell et al. 2005; TIFP 2006). The initial boundary condition for water surface elevation at the downstream boundary should ensure that all nodes in the model are inundated; the spin-down procedure gradually lowers the water surface elevation boundary condition to the target elevation. Similarly, the eddy viscosity parameter is initially specified a magnitude or more higher than the final eddy viscosity. Changing, or fine-tuning, the eddy viscosity and the bed roughness provides a means of calibrating model output to match field data that may include water surface elevation (minimally at the upstream boundary), water surface profiles and measurements of depth and velocity at discrete locations (Donnell et al. 2005; TIFP 2006).

Roughness specification is straight-forward (Prasuhn 1987; Arcement and Schneider 1989) when a substrate map of the site is available to indicate spatial distribution of substrate classes defined by predominant grain size. RMA2 allows automatic variation of roughness according to depth (Donnell et al. 2005); however, specification of a constant roughness may be adequate in models with homogeneous substrate (Osting et al. 2004a).

Eddy viscosity can be specified directly by the user or assigned dynamically (Donnell et al. 2005). The RMA2 user's manual and other studies (Richards 1990; Freeman 1992) provide suggestions for eddy viscosity values based upon flow conditions and element size; however, the suggested range is large. The Peclet and Smagorinsky methods allow automatic eddy viscosity assignment that varies in space according to local velocity and local node spacing. RMA2 models applying the Smagorinsky method were not found within literature; however, a number of applications for Peclet number are reported. Use of Peclet numbers between 4 and 40 are recommended (Berger 1990; Richards 1990; Freeman 1992; Donnell et al. 2005) where the relationship between Peclet number and eddy viscosity is

$$Pe = \frac{u\,L_4}{\frac{v_e}{\rho}} \qquad (3.1)$$

where, Pe = Peclet number

u = local velocity

L_4 = local node spacing

ν_e = local eddy viscosity

ρ = density.

The Peclet number, generally used for heat transfer problems, is a dimensionless number relating a characteristic length and velocity (heat convection) to diffusivity (heat conduction). Vreugdenhil (1982) predicts oscillations in a river sediment model based upon a cell Peclet number that relates the cell length scale and velocity to a numerical diffusion coefficient. Similarly, use of Peclet number less than 40 in the RMA2 model (Donnell et al. 2005) ensures 1) that node spacing is distant enough that momentum is dominated by advection and 2) eddy viscosity is sufficiently large to prevent oscillations. Use of Peclet number greater than 4 (Richards 1990) ensures that eddy viscosity is not so high that water exhibits a consistency like maple syrup. Berger (1990) states that use of a small eddy viscosity value results in better mass conservation; however, Berger (1990) also shows model instability for a single element when the Peclet number is between 3 and 5.

3.2 Continuity as indicator of velocity uncertainty

Since RMA2 conserves mass throughout model domain but not necessarily within each element (Richards 1990), continuity has been used within the model boundaries to identify areas of instability (Richards 1990; Freeman 1992; King 1992; Donnell et al. 2005; Osting et al. 2004b). Deviation of continuity, the percent difference of flow rate at a cross-section compared to flow rate at a baseline cross-section (typically at the inflow boundary specification), is an indicator of velocity uncertainty. For subcritical flows, continuity deviation can generally be attributed to deviations in predicted velocity since velocity gradients are several magnitudes larger than water surface elevation gradients across a section. A number of exceptions can be noted, including flow near submerged structures; however, flow conditions exhibiting large gradients in water surface elevation are generally non-hydrostatic conditions where the shallow water equations are not applicable. Gradients of RMA2 water surface elevation predictions large enough to influence continuity result from undesirable spurious oscillations that should be mitigated by adjusting eddy viscosity (Freeman 1992).

The RMA2 user manual states that a model exhibiting continuity deviations less than 3% between cross-sections is satisfactory (Donnell et al. 2005). King (1992) states that 5% deviation from continuity is too much for transient models used for water quality purposes and that 2.5% is the maximum deviation that should be allowed. The average velocity uncertainty across a section is equivalent to the continuity deviation if no other factors influence continuity; therefore, the continuity deviation should be considered the minimum percent of velocity uncertainty.

3.3 Previous studies of RMA2

Freeman (1992) conducted a series of tests to evaluate RMA2 output. Split-quadrilateral finite elements (arranged in alternating or regular, cf. Figure 1.1, patterns) most consistently maintain continuity in steady-state RMA2 model output. Continuity was best maintained when complex bathymetric features are represented by many nodes and when eddy viscosity was specified according to Peclet numbers between 15 and 40 (Donnell 2005). For depth reductions or depth increases between nodes where rise to depth ratio is 0.125 and where slope (rise to length ratio) was less than 0.10, RMA2 maintained continuity for all cross-sections within 5%. For steeper slopes up to 0.20, RMA2 maintained continuity within 10% (Freeman 1992). For abrupt width reductions and contractions (the change representing 40% of maximum width), Freeman (1992) showed that node spacing (in both x and y directions) resolving 10% of the width change maintained continuity within 10%. For the slope tests, lower values of eddy viscosity produced more stable results; for the horizontal contraction and expansion tests, higher values of eddy viscosity produced more stable results (Freeman 1992). Increasing resolution produced more stable results for all test cases (Freeman 1992).

Similarly, Richards (1990) showed that a high RMA2 eddy viscosity value is needed to predict observed flow separations around a dike. For a dike modeled so that node spacing resolves half of the change in width (the two-element dike), continuity is maintained within 5%. Separation length, the distance the flow disturbance persists downstream of the dike, only matches observed physical model results by using closer node spacing of one-quarter of the change in width. Although stable solutions are achieved using Peclet numbers higher than 30, results with Peclet number of 4 (higher eddy viscosity) produced model predictions that better matched observations of separation length. This result is consistent with Freeman's (1992) finding that higher eddy viscosity values (lower Peclet numbers) produce more stable results for lateral contractions.

3.4 Scaling study

The Freeman (1992) and Richards (1990) models are different in node spacing and flow magnitude compared to each other and also compared to models applied in the Brazos River study (Osting et al. 2004a). The Freeman study, modeling hydraulics of the Mississippi River, employs high flow rates (500,000 cfs), large spatial domains (length: 21,000 feet; width: 1,000 feet) and large node spacing (125 feet or more). Richards (1990) developed a model for flows less than 3 cfs and node spacing of roughly 6 inches to compare model output to observations made in a small physical model. For the Brazos River, Texas, Osting et al. (2004a) utilized a model with irregular node spacing of roughly 16 feet for flows ranging from 700 to 7000 cfs.

To compare models having different ranges of flow, node spacing and velocity, Froude number modeling (Prasuhn 1987) is used to translate between ranges. Translation is needed so that recommendations and uncertainty quantifications described by Freeman (1992) can be extrapolated with respect to vertical contractions and expansions, and with respect to specification of eddy viscosity.

Error norm statistics were calculated for each model test scenario to facilitate comparison between scenarios. Where error, e_i, is defined as

$$e_i = \psi_i - \overline{\psi}_i \qquad (3.2)$$

where $\overline{\psi}_i$ = predicted solution (continuity at a section)

ψ_i = exact solution (continuity is 100%)

i = cross-section

the $\|e\|_{L_2}$ (or *L-two*) Root Mean Square (RMS) error norm is defined as

$$\|e\|_{L_2} = \left[\frac{1}{m}\left(\frac{1}{\psi_{\max}{}^2}\sum_{i=1}^{m}|e_i|^2\right)\right]^{\frac{1}{2}} \qquad (3.3)$$

where m = number of cross-sections.

The $\|e\|_{L_1}$ (or *L-one*) error norm represents an average error and is defined as

$$\|e\|_{L_1} = \frac{1}{m\psi_{\max}}\sum_{i=1}^{m}|e_i|\,. \qquad (3.4)$$

The $\|e\|_{L_\infty}$ (or *L-inf*) maximum error norm represents the maximum error occurring in the solution and is defined as

$$\|e\|_{L_\infty} = \frac{1}{\psi_{\max}}\max|e_i|\,. \qquad (3.5)$$

Errors norm statistics are reported as a percentage of continuity.

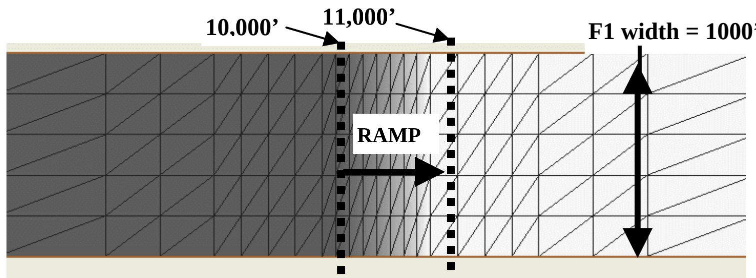
To first verify that the recent version of RMA2 (v4.56) produces comparable results to the version used by Freeman in 1992 (RMA-2V, version unspecified, possibly v4.25), Freeman's (1992) most refined regular grid with 8 elements on the face of a 500' long and 50’ high vertical contraction (0.10 slope) was duplicated for this thesis (Figure 3.1a, Figure 2.1a). Using the same input parameters and boundary conditions, RMA2 (v4.56) predictions are nearly identical to Freeman’s. Continuity on cross-sections located on the slope face (located between 10,000 ft and 11,000 ft) is within 0.5% of the inflow (Figure 3.2a compared to Figure 3.2b, i.e., Figure 36a of Freeman, 1992) when eddy viscosity is set to 5 lb-sec/square foot. Freeman found that using 5 lb-sec/square foot resulted in the least number of oscillations and lowest continuity deviations (Table 3.1 and Figure 3.3a, F1 mesh); however, based upon node spacing, velocity and eddy viscosity, the Peclet number for elements near the downstream boundary is 212. This value is much larger than the maximum of 40 that was recommended in the user’s manual (Donnell et al. 2005). Using a higher eddy viscosity value of 125 lb-sec/square foot (resulting in a Peclet number of 8.5 which is within the recommended range) results in higher continuity deviations near 2% (Freeman 1992).

Testing the same model with the only change being a more abrupt vertical contraction (0.20 slope) results in maximum continuity deviation of 1% (Table 3.1 and Figure 3.3b, F1 mesh). The worsening of continuity can be attributed to either the increase in slope above hydrostatic limitations, or to the reduction in resolution across the face of the slope. Whereas Freeman used eight elements to represent the 0.10 slope, only 4 elements represent the 0.20 slope. For both the 0.10 and 0.20 slope cases, node spacing was reduced compared to the F1 mesh so all finite elements were uniform in dimension, 50 feet laterally x 62.5 feet in the direction of flow (Figure 3.1b, R2 mesh). The increase in resolution improved model stability and reduced continuity deviations; no difference greater than 0.2% was observed in continuity compared to the previous model runs (Table 3.1 and Figure 3.3a and 3.3b, R2 mesh).

To determine whether RMA2 predicts consistent results across scales, the entire model domain is reduced by a factor of 3.31 feet / 50 feet (= 0.0662). The factor corresponds to a desired depth of 3.31 feet (1.01 meters) in areas where the Freeman (1992) models are 50 feet deep. The resulting node spacing is 3.31 feet laterally x 4.14 feet in the direction of flow (Figure 3.1b, SMR2 mesh). Froude number modeling (e.g. Prasuhn 1987) was used to scale Freeman’s flow rate to a comparable flow rate.

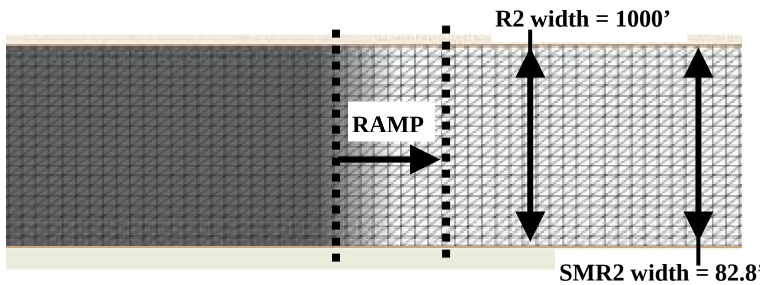
$$\mathrm{Q} = \left(500{,}000\ \mathrm{cfs}\right)(0.0662)^{5/2} = 339.66\ \mathrm{cfs}$$

For consistency with the value used in the best Freeman model, eddy viscosity is assigned according to scaled velocity and scaled element length so that the Peclet number is 212. The resulting eddy viscosity is 0.0852 lb-sec/square foot. For all scenarios (both expansion and contraction), continuity and norm statistics were worse than shown by Freeman (1992) indicating that the model is not consistent across scales (Tables 3.1 and 3.2, Figures 3.3 and 3.4, SMR2). Adjusting eddy viscosity so Peclet number is 30 (between 15 and 40 as recommended by Donnell et al. 2005) does not improve continuity for the contraction (Table 3.1, SMR2). For the expansion scenarios where Peclet numbers are within recommended values, continuity is improved and is comparable to continuity for Freeman’s full-scale models (Table 3.2, SMR2).



F1 Freeman grid ("Res8")
250' x125' (LxW) elements
62.5' x 125' elements on ramp

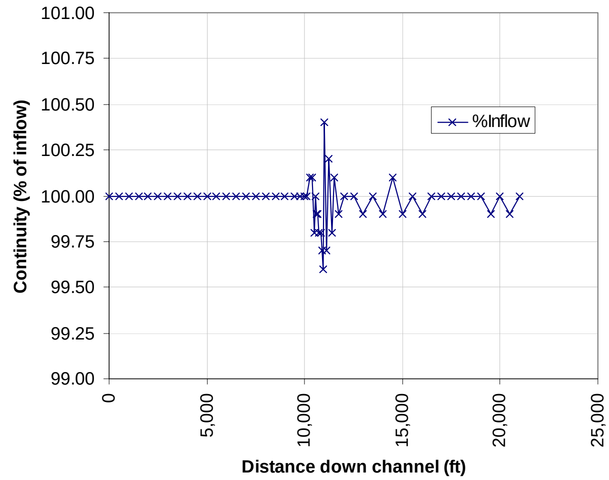
(a) Freeman (1992)



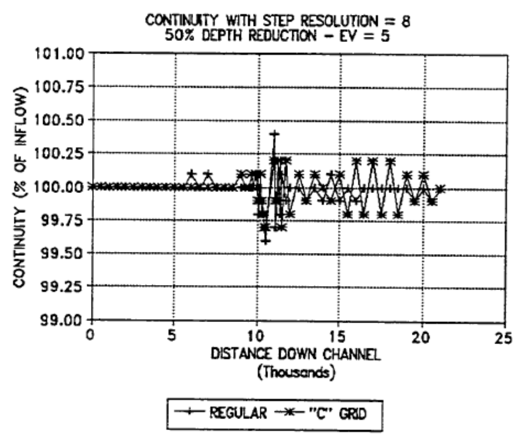
R2 Modified F1 grid, regular 62.5'x50' elements
SMR2 Modified R2, regular 4.14' x 3.31' elements

(b) Modified mesh

Figure 3.1 - Test case finite element meshes



(a) duplicate run (regular grid)

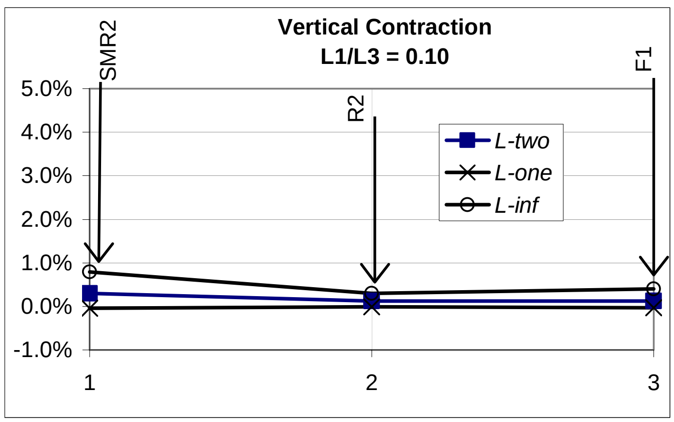


(b) Freeman (1992) Figure 36a

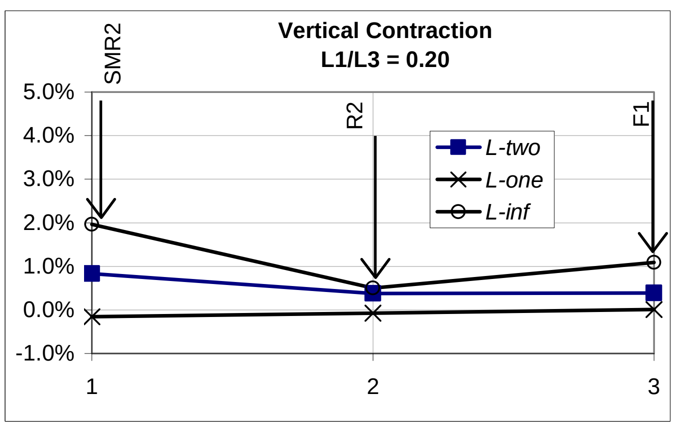
Figure 3.2 - Duplication for this thesis of Freeman (1992) model output

Table 3.1 - Error norm table for vertical contraction

Run	Peclet	Maximum Continuity Difference	*L-two* norm (RMS)	*L-inf* norm (max)	L1/L3	L1/L2 rise:run	L4/L3 length:depth
F1	212	0.40%	0.12%	0.40%	1	0.1	0.125
	212	1.10%	0.39%	1.09%	2	0.2	0.375
R2	212	0.30%	0.12%	0.30%	1	0.1	0.125
	212	0.90%	0.38%	0.89%	2	0.2	0.375
SMR2	212	0.80%	0.29%	0.79%	1	0.1	0.125
	30	1.20%	0.34%	1.19%	1	0.1	0.125
	8.5	1.40%	0.39%	1.38%	1	0.1	0.125
	212	2.00%	0.84%	1.96%	2	0.2	0.375
	30	1.70%	0.73%	1.67%	2	0.2	0.375
	8.5	2.10%	0.76%	2.06%	2	0.2	0.375



(a) 0.1 slope

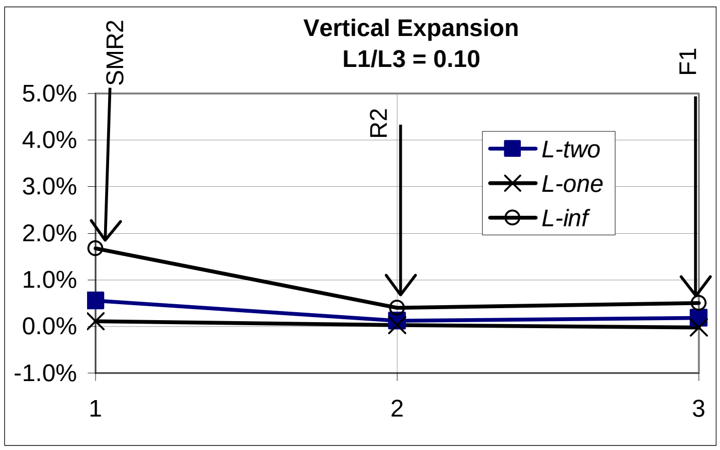


(b) 0.2 slope

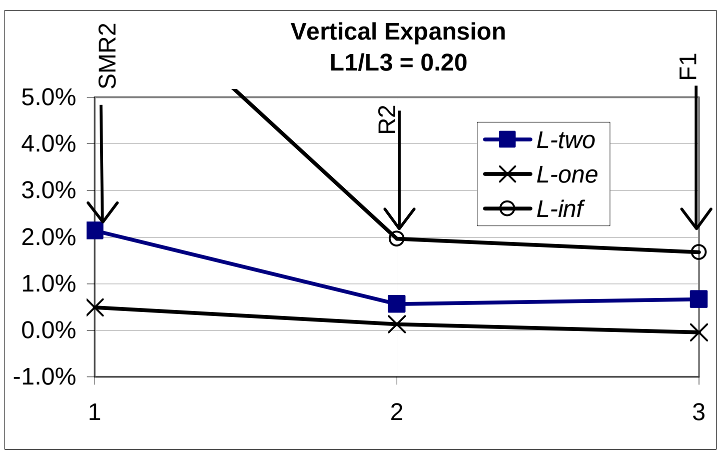
Figure 3.3 – Norm errors for vertical contraction

Table 3.2 – Error norm table for vertical expansion

Run	Peclet	Maximum Continuity Difference	*L-two* norm (RMS)	*L-inf* norm (max)	L1/L3	L1/L2 rise:run	L4/L3 length:depth
F1	212	0.50%	0.18%	0.50%	1	0.1	0.06
	212	1.70%	0.67%	1.67%	2	0.2	0.09
R2	212	0.40%	0.13%	0.40%	1	0.1	0.06
	212	2.00%	0.56%	1.96%	2	0.2	0.09
SMR2	212	1.70%	0.56%	1.67%	1	0.1	0.06
	30	0.50%	0.11%	0.50%	1	0.1	0.06
	8.5	0.90%	0.23%	0.89%	1	0.1	0.06
	212	8.60%	2.14%	7.92%	2	0.2	0.09
	30	3.30%	0.62%	3.19%	2	0.2	0.09
	8.5	1.50%	0.32%	1.48%	2	0.2	0.09



(a) 0.1 slope



(b) 0.2 slope

Figure 3.4 - Norm errors for vertical expansion

3.5 Summary of uncertainty in RMA2

Uncertainty in RMA2 model predictions was investigated based upon previous studies and for a series of test scenarios using continuity as the measure of accuracy. Best continuity is achieved for bathymetric conditions where slope is less than 0.10, for node spacing and eddy viscosity combinations where Peclet number is between 15 and 40 and for node arrangements where changes in bathymetry are resolved using many nodes. When these conditions are not met, continuity deviations can be in excess of 10%, even as high as 50%, on a slope where node spacing is coarse (Freeman 1992). When appropriate conditions for node spacing and eddy viscosity are met, continuity deviations as high as 2% were still observed. Continuity deviations are highest for vertical contractions with slope greater than 0.20, but are most sensitive to eddy viscosity specification for the vertical expansion case with slope greater than 0.20.

Specification of eddy viscosity so that Peclet number is between 15 and 40 (Donnell et al. 2005) was found to strike a good balance for all cases. Model results exhibited less continuity deviation for high Peclet numbers on slopes; whereas, Peclet numbers smaller than 15 resulted in less continuity deviation for abrupt changes in width. Model results did not exhibit poor continuity for either case when Peclet number was within the recommended range (Freeman 1992).

The model was sensitive to scaling. All dimensions (node spacing, depth, flow) of the SMR2 model were scaled according to Froude number such that the SMR2 model should have exhibited the same continuity patterns as the R2 model. However, compared to the R2 model, the SMR2 model exhibited higher (worse) continuity and was more sensitive to eddy viscosity.

4.0 Terrain analysis of natural rivers

4.1 Natural river bedforms

Section 3 discusses uncertainty in model predictions for simple test cases. The node arrangement in each test case are straight sections without curves and have uniform bathymetry and regular grid spacing. Node arrangements for natural river models are different in that they follow natural morphology.

Natural rivers are collections of similar, but not identical, repeating components. Typical components include 1) meandering planform, 2) asymmetrical u-shaped cross-section that deepens on the concave side of a bend, 3) riffle-to-pool bedforms and 4) erosion and deposition zones (Nanson and Croke 1992; Rosgen 1994; Leopold 1997; Brierley et al. 2002; TIFP 2006). Heterogeneity becomes more apparent as a river is discretized into smaller and smaller components (Brierley et al. 2002). For example, river meanders vary in length, curvature and amplitude (i.e., sinuosity) according to sedimentary material encountered (Rosgen 1994); significant deflections in river path and deviations from pattern are possible near an encounter with a high valley wall. Within bounds of one meander, the river cross-section may change from asymmetrical in a bend (deeper on the concave side of the bend) to symmetrical in a straight section back to asymmetrical in the next bend (Jia and Wang 1999); however, significant variations to this pattern are possible near bedrock outcrops, interfaces of sedimentary material types and tributary confluences.

A hydraulic model mesh developed from high-resolution bathymetric data will exhibit local variations in terrain . The lateral dimensions relevant to instream flow models, which can be as small as 2.3 meters from the ecological perspective (see section 1), can be contrasted to large Texas coastal plain river channels with bankfull widths of 50 to 100 meters. A 100-meter-wide river exhibits a high level of heterogeneity when discretized into 2.3-meter increments. Local bathymetric structures are exemplified in the form of debris piles, boulders, bank slough material, dunes, scour holes, tires, refrigerators and many other natural and unnatural forms (TIFP 2006); all such structures have potential to influence flow patterns in their vicinity.

4.2 Dimensional analysis

Model test cases noted in Section 3.3 encompass a limited range of possible morphological forms compared to terrain typically found in a model of a natural river. To compare node arrangements with respect to slope, orientation, depth and spacing, a dimensional analysis is used to characterize the range of local slopes that exist in natural bathymetry. Seven parameters with dimensions of length and time (Figure 4.1) characterize model input (inflow, eddy viscosity, node arrangement) and output (velocity and depth); these parameters are chosen to relate model configuration to the hydrostatic assumption of the shallow water equations. The parameters include gravity (g), vertical rise along a slope (L_1), longitudinal run along a slope (L_2), depth (L_3), velocity (*u*), grid size (L_4) and eddy viscosity (ν_e). These parameters can all be treated with respect to two dimensions, length and time. Five parameters describe the natural environment and two parameters describe dimensions important for execution of the hydraulic model. All parameters are considered independent for the purposes of this analysis; while relationships between these parameters do exist based upon the classical specific energy concepts (e.g., Prasuhn 1987), those relationships can be analytically determined and compared to node configuration and output of the 2D numerical model. The system is assumed to be infinitely wide so that sidewall effects can be neglected.

The parameters *u* and L_3 are shown in Figure 4.1 as downstream of the vertical contraction because for subcritical flow the downstream conditions control the water surface. However, in the case of a vertical expansion, *u*, and L_3 should be defined upstream since upstream conditions control the water surface in an expansion.

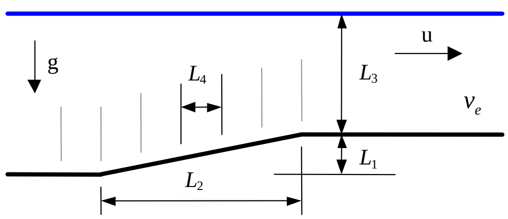


Figure 4.1 – Flow system and independent parameters

After Buckingham (1914) and hydraulic textbooks (e.g., Prasuhn 1987; Roberson and Crowe 1993), this system exhibiting seven independent parameters expressed in 2 dimensions can be represented with 5 equations. The hydraulic definition of the Froude number (e.g., Prasuhn 1987), Fr, is one of the non-dimensional parameters:

$$Fr = \frac{u}{\sqrt{gL_3}} \tag{4.1}$$

In physical flow systems where gravity is the predominant driving force, as in open channel free surface flow, the Froude number characterizes the relationship between flow velocity and gravity forces acting upon the water column. Geometry scaling in this thesis will be with respect to water depth, L_3. The slope of the vertical contraction is the ratio of vertical rise, L_1, to longitudinal distance (run) over which the rise occurs, L_2.

$$\frac{L_1}{L_2} \tag{4.2}$$

The ratio of vertical rise (or fall), L_1, to the flow depth, L_3, quantifies the magnitude of vertical change relative to hydraulic conditions, and can be conveniently related to natural conditions on a site.

$$\frac{L_1}{L_3} \tag{4.3}$$

Relating the hydraulic model to the natural system, the ratio of grid cell spacing in the direction of flow, L_4, to the depth of the cell, L_3.

$$\frac{L_4}{L_3} \tag{4.4}$$

The Peclet number, described in section 3.1 as useful for assigning eddy viscosity value based upon velocity and element length, includes both dimensions of length and time.

$$Pe = \frac{uL_4}{\frac{v_e}{\rho}} \tag{4.5}$$

4.3 Bathymetric terrain and flow characteristics within a calibrated natural river model

A number of node configurations are identified in Section 3 that cause uncertainty in the RMA2 model. The configurations include slopes (vertical contractions and expansions) and abrupt changes in width; however, no additional variability is exhibited in the bathymetry of the test models. This simplicity is in contrast to bathymetry of a typical natural river model where the terrain (i.e., the collection of surface characteristics) is highly variable. The purpose of this section is to quantify the variability and to determine the percent area of a natural river model that exhibits node arrangements with potential for continuity deviations (as identified in Section 3). Terrain and flow characteristics were determined for each wetted element of a calibrated steady-state RMA2 model. Characteristics include the dimensional analysis parameters described in Section 4.2 and additionally include element orientation (aspect) relative to the flow direction. The natural river model was used for an instream flow analysis and encompasses a complete meander wavelength within a 4.3 mile Brazos

River, Texas, reach (Osting et. al 2004a), shown in Figure 4.2. The channel is approximately 300 feet wide (100 meters). The mesh is composed of 48,283 nodes arranged so finite elements are approximately 22 feet wide by 38 feet in the direction of flow (7m x 12m); the node spacing varies and is finer in areas with complex bathymetry.

Terrain statistics are shown in Figure 4.3. All statistics were derived in the direction of flow based on model output velocity vectors. The Froude number, determined for each finite element, is less than 0.37 for 99% of the elements (Figure 4.3a); this is lower than supercritical (Fr = 1.0) as well as lower than the value of 0.6 that causes instability in RMA-2 (Donnell et al. 2005). Although flow conditions in this model do not approach the upper limit, it is worth noting that this is an artifact of analyzing model output; the model begins to become unstable if solving at Froude numbers higher than 0.6 (Donnell et al. 2005) and thus will only produce a stable output at lower Froude numbers.

A constant eddy viscosity value of 200 Pascal-seconds was applied uniformly to all elements in the model; this was the lowest eddy viscosity that achieved stable model results. The model feature was not used whereby eddy viscosity is automatically assigned; convergence problems exhibited during model development were addressed by specifying eddy viscosity uniformly. Therefore, it is not surprising that fifty-six percent of elements fall outside of the recommended Peclet number range of 15 to 40 (Freeman 1992; Donnell et al. 2005); one percent of elements have Peclet numbers greater than 40 (Figure 4.3b). Considering Richard's (1990) findings that show best results for Peclet numbers above 4, twenty percent of the elements have Peclet numbers less than 4. To ensure the Peclet number recommendations are followed in future models, eddy viscosity should be automatically assigned by the model according to each element's length, velocity and Peclet number (Donnell et al. 2005); alternatively, eddy viscosity could be assigned using a Smagorinsky coefficient between 0.094 and 0.2 (Donnell et al. 2005).

Median velocity within the model domain is 0.4 m/s (Figure 4.3c), median depth (at element centroid) is 1.09 meters (Figure 4.3d) and median element length is 6.77 meters (Figure 4.3e). Median change in elevation across each element in the velocity direction is near zero (Figure 4.3f). The median of all rises (where L1 is greater than zero) is 0.07 meters and the median of all falls (L1 is less than 0) is 0.06 meters (Figure 4.3f). Five percent of elements have falls greater than 0.33 m and five percent have rises greater than 0.39 m.

The ratio of rise (or fall) to depth (L1/L3) is a measure of the amount of vertical expansion or contraction on the basis of depth. Ten percent of elements have a rise to depth ratio greater than 0.42 (Figure 4.3g). Five percent of elements have a slope (rise to length ratio, L1/L3) in the direction of flow greater than 0.1 and 2.6% of the elements exhibited slopes between 0.1 and 0.2; 1.7% exhibit slopes greater than 0.2 (Figure 4.3j).

Freeman (1992) shows continuity errors approach 5% for elements having a rise to depth ratio greater than 0.25 and slopes greater than 0.1; continuity errors exceed 10% when slope is greater than 0.2. Within the Brazos River model, elements satisfying both the rise to depth ratio condition and the slope greater than 0.1 condition comprise 1.8% of the total wetted area; therefore, 1.8% of the model area likely has continuity (velocity) errors of 5%.

The length-to-depth ratio (L4/L3) is less than 5.0 for 36% and less than 1 for 1.6% of elements in the Brazos River model (Figure 4.3h). Differences have been documented between hydrostatic and non-hydrostatic predictions (of pressure on seiche wave fronts) where wavelength to depth ratio is between 2 and 20 (Chen 2005); however, both Richards (1990) and Freeman (1992) find the best model performance when length to depth ratio is near 1.0. Additionally, RMA2 has predicted reasonable velocity fields at ratios as small as 0.08 (Crowder and Diplas 2000); the models employed in that particular study were carefully calibrated with understanding that the model was being applied outside of applicable assumptions. The length-to-depth ratio of elements within the Brazos River model does not appear to be unreasonable.

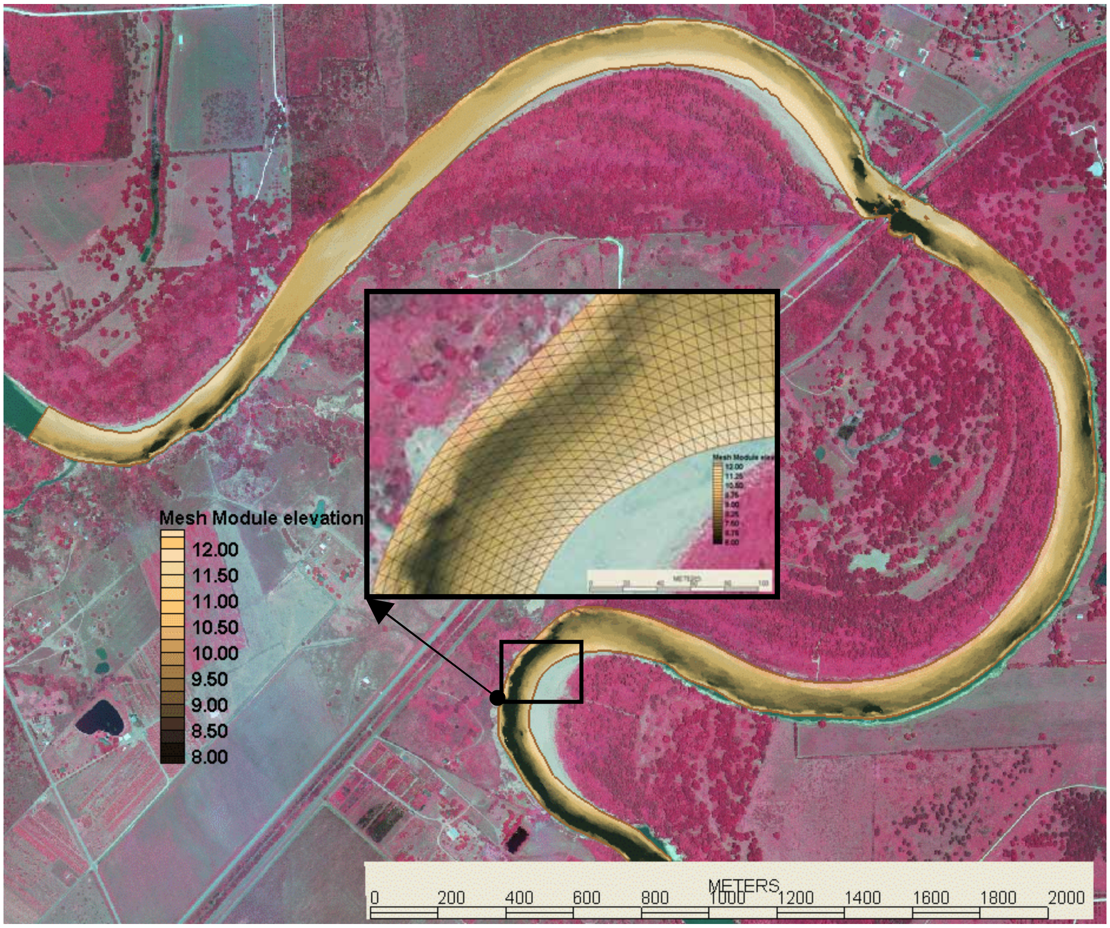


Figure 4.2 – Plan view of Brazos River model with bathymetric color contours

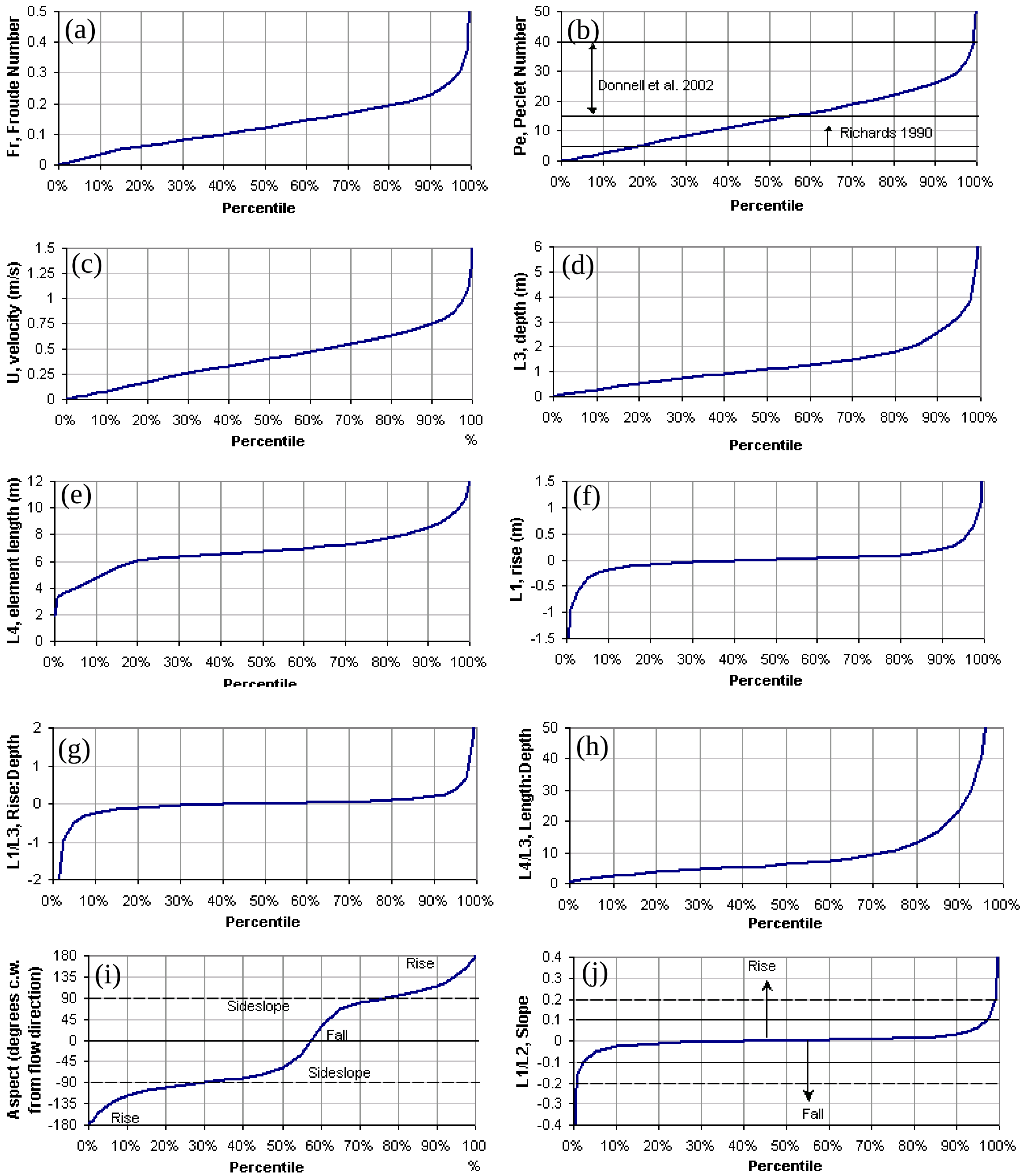


Figure 4.3 – Terrain statistics of Brazos River model

Aspect is defined in this thesis as the orientation of each element face with respect to flow direction, where zero degrees is defined as where the vector normal to the element face is parallel to the velocity vector (i.e., the element faces directly downstream). The distribution of aspect illustrates the natural cross-sectional shape of the river channel, where elements having aspect transverse to the direction of flow outnumber elements with aspect in the direction of flow (Figure 4.3i). Put another way, most elements face toward the center of the channel (zero or +/-180 degrees).The relationship of slope and aspect is investigated on an element-by-element basis for the Brazos River model (Figure 4.4). Each dot represents one element. A dot positioned at –15 degrees aspect represents an element affecting a vertical expansion having a slope value according to its position along the y-axis and having a slope face pointing to the left of the velocity vector. Aspect of –135 degrees represents a vertical contraction. Aspect of –90 degrees or +90 degrees represent an element whose face is parallel to the flow direction. An abrupt horizontal contraction is characterized by a steep slope and aspect of +/-180 degrees (if the downstream area is dry); a horizontal expansion is characterized by a steep slope and aspect of 0 degrees (if the upstream area is dry). Although only wetted elements are considered in the figure, a steep submerged element with aspect perpendicular to the flow direction may impart similar characteristics as the abrupt expansions and contractions.

Richards (1990), Johns (1991), Freeman (1992) and Stansby and Zhou (1998) investigated only a small portion of the range of slope v. aspect possibilities exhibited in the Brazos River model (Figure 4.4). Johns (1991), Freeman (1992) and Stansby and Zhou (1998) tested the 0 and 180-degree aspect cases for varied slopes. Richards (1990) tested only 0-degree aspect case with slope of 1.0 (a total contraction or total expansion). So inferences made regarding uncertainty in test cases only apply to a limited selection of elements within a model developed on a natural river; a model where aspect of elements exhibit variability.

4.4 Summary of terrain analysis

Morphology of natural river channels exhibit variability; therefore, models of natural rivers exhibit variability in terrain. Analysis of the submerged terrain within a calibrated model demonstrated that variability. Less than 3% of the total area of the calibrated model exhibited terrain characteristics that in the test cases showed potential to cause continuity deviations. More than 50% of the model area, however, exhibited Peclet numbers lower than the recommended range; based upon the test cases, low Peclet numbers (high eddy viscosities) were most likely to cause continuity deviations in areas with abrupt lateral expansions or contractions. With exception of six obstructions representing bridge columns, very few elements exhibited high slope and aspect near 0 degrees. Overall, based upon the terrain and flow characteristics as well as model test cases described in Section 3, over 97% of the total area within the Brazos River model should have continuity deviations less than 2%.

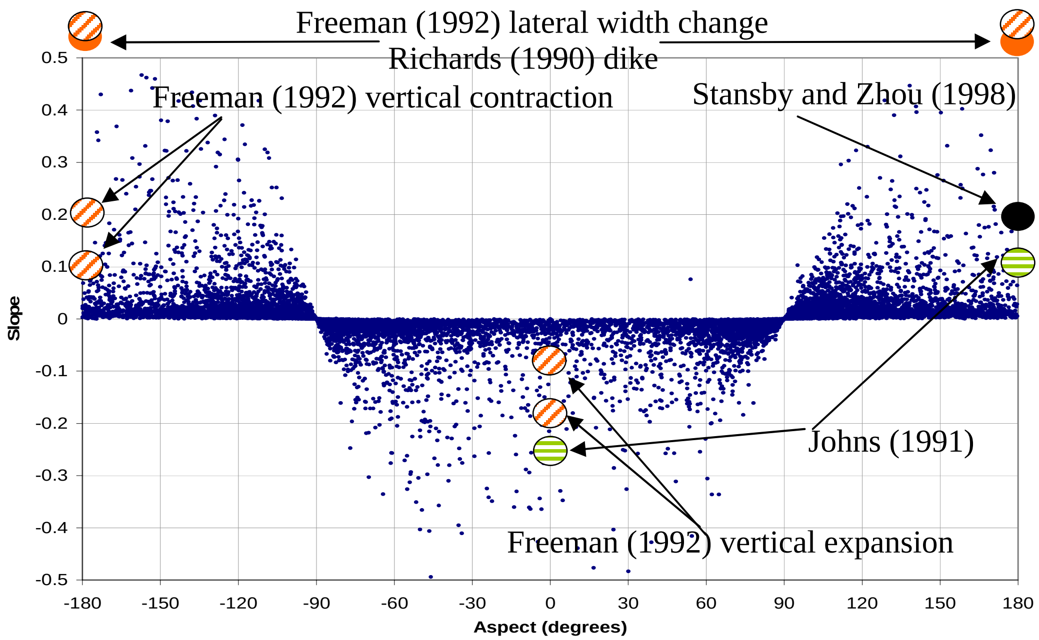


Figure 4.4 - Brazos River model, slope vs. aspect

5.0 Conclusions

Potential for uncertainty in 2D shallow water hydrodynamic model predictions arises from several factors associated with model formulation limitations, input data quality and model implementation. The ability of shallow water equation models to predict spatially-distributed patterns of velocity and depth make them useful for aquatic habitat studies (Leclerc et al. 1995); however, the spacing between model nodes is desired to be similar to the size of field-sampled habitat, approximately 10 meters square. Close node spacing reveals bathymetric variability that is potentially more complex than the shallow water equations are formulated to consider.

Uncertainty stemming from use of the shallow water equations and from accuracy limitations in field data are described in Section 2. Two issues arise when considering proximity of model nodes to bathymetry data. First, when field bathymetric data is sparse in the vicinity of each computational node, assignment (interpolation) of elevation (z) to each node is based upon distant data points. Bathymetry data should be collected with sufficient spacing to capture the variation that is desired in the model. Second, when field data is dense, local heterogeneity of the river bed surface may be incorporated into the nodal arrangement leading to local conditions that the model was not formulated to solve. The condition with greatest potential to increase model uncertainty is a vertical expansion or contraction with a steep slope; this condition can affect vertical pressure gradients and flow separations thus violating the non-hydrostatic pressure assumption.

Positional accuracy of input data (in the x, and y directions) is 1 meter at best when multiple datasets of GPS data are combined, unless survey-grade, differentially-corrected, post-processed positional data is measured. Depth accuracy is 15 cm when bathymetry data is measured using a boat-mounted echosounder. Water surface elevation measurements, are accurate to within 2 cm at best; therefore, site boundaries should be chosen in the field (i.e., separated by sufficient stream wise distance) to ensure water surface slopes can be measured within desired accuracy. Flow rate measurements used for model input are accurate to within 2% and velocity point measurements are accurate to within 3%. The single most important source of uncertainty in field data is depth data. Because of the 15 cm vertical accuracy of depth sounders, caution should be exercised using these devices where depth predictions approach the data accuracy or where more accurate depth predictions are required. Where more accurate data is required, more resources (personnel, time, money) should be allocated to conduct a bathymetry survey using more accurate methods that could include a total station; survey-grade, differentially-corrected, post-processed GPS; or instrumentation to correct for boat motions. Test cases developed for this thesis (Section 3.4) as well as previous studies (Section 3.3) have shown the potential for RMA2 continuity (velocity continuity errors) in excess of 5% near areas exhibiting slopes greater than 0.1 or exhibiting abrupt width changes; this is true for models where bathymetry is not complex (Richards 1990; Freeman 1992). Consistent with Donnell et al. (2005) recommendations, eddy viscosity values and node spacing resulting in a Peclet number between 15 and 40 do increase model stability and do reduce deviations in continuity. Use of RMA2's automatic eddy viscosity assignment feature is recommended.

Analysis of submerged terrain within a calibrated RMA2 model (Osting et al. 2004a) revealed geometric characteristics suitable for a shallow water equation model (Section 4). The elemental length-to-depth ratio was greater than 1.0 for 98% of the model area, and element slope was less than 0.10 for 95% of the model area. For those elements with a slope greater than 0.1 and a length-to-depth ratio of 0.125, uncertainty was determined to be applicable to 2.5% of the total domain, with those error-prone areas having potential uncertainty as high as 2% for continuity.

Despite studies that show trends in instream aquatic habitat area are not significantly affected by uncertainty in the hydraulic models (Bhosle 2004), uncertainty in instream flow recommendations (and therefore in hydraulic models) should be minimized to the extent possible (Bovee et al. 1998; NRC 2005; TIFP 2006). Minimization of uncertainty in hydrodynamic models applied to water quality and sediment transport studies is similarly a necessary objective (King 1992; Pasternack et al. 2006).

To minimize uncertainty in shallow water equation model predictions, the following general guidelines are recommended:

- Locate positional data (bathymetric, calibration or validation) using the most accurate equipment available
- Adjust node spacing and grid orientation to minimize areas known to cause model instabilities
- Ensure smooth elevation transitions between model nodes, particularly in areas with high bathymetric gradients
- Minimize local areas with slopes greater than 0.1 (rise-to-length ratio)

To minimize uncertainty in RMA2 predictions, the following specific guidelines are recommended (King 1992; Lane and Richards 1999; Katopodis 2003; Donnell et al. 2005):

- Node spacing should not be nearer to each other than the depth of flow
- The angle between nodes in a finite element mesh should be between 45 and 135 degrees
- The change in node spacing should be no larger than 30%
- Spacing should be closest in the direction of strongest depth or velocity gradient
- The area of adjacent finite elements should not differ by more than 50%
- Length to width ratio of a finite element should not exceed 10
- Triangular or quadrilateral finite elements shapes should not be highly distorted
- Bathymetric elevations of finite element corner nodes should lie in a plane (use of triangular elements is recommended)
- Finite element edge depths should not change more than 20%
- Boundary elements should not exhibit angles greater than 25 degrees.
- Use the built-in model features to automatically assign eddy viscosity.

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Vita

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